Science of the Total Environment 627 (2018) 756–769

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Response of a multi-stressed Mediterranean river to future climate and socio-economic scenarios

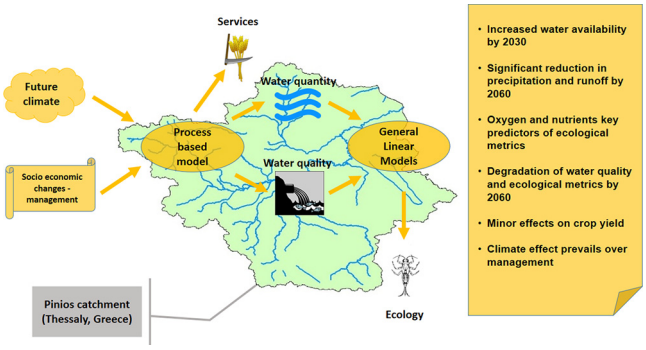
Konstantinos Stefanidis *, Yiannis Panagopoulos, Maria Mimikou

Center for Hydrology and Informatics, Department of Water Resources and Environmental Engineering, School of Civil Engineering, National Technical University of Athens, Greece

HIGHLIGHTS

- We examined the response of the Pinios river to future world scenarios.
- Abiotic state was assessed with the Soil and Water Assessment Tool.
- Macroinvertebrate metrics were assessed by employing empirical modelling.
- Results predict degradation of biotic and abiotic state by 2060.
- Climate effects prevail over future management in the basin.

GRAPHICAL ABSTRACT


Services
Future climate
Water quantity
Process based model
General Linear Models
Water quality
Socio economic changes - management
Pinios catchment (Thessaly, Greece)
Ecology
Increased water availability by 2030
Significant reduction in precipitation and runoff by 2060
Oxygen and nutrients key predictors of ecological metrics
Degradation of water quality and ecological metrics by 2060
Minor effects on crop yield
Climate effect prevails over management

ARTICLE INFO

Article history:
Received 27 July 2017
Received in revised form 27 January 2018
Accepted 27 January 2018
Available online 2 February 2018

Keywords:
Catchment modelling
Ecological response
Ecosystem services
Empirical modelling
Future world scenarios
Macroinvertebrates

ABSTRACT

Streams and rivers are among the most threatened ecosystems in Europe due to the combined effects of multiple pressures related to anthropogenic activities. Particularly in the Mediterranean region, changes in hydromorphology along with increased nutrient loadings are known to affect the ecological functions and ecosystem services of streams and rivers with the anticipated climate change being likely to further impair their functionality and structure. In this study, we investigated the combined effects of agricultural driven stressors on the ecology and delivered services of the Pinios river basin in Greece under three future world scenarios developed within the EU funded MARS project. Scenarios are based on combinations of Representative Concentration Pathways and Shared Socioeconomic Pathways and refer to early century (2030) and mid-century (2060) representing future climate worlds with particular socioeconomic characteristics. To assess the responses of ecological and ecosystem service indicators to the scenarios we first simulated hydrology and water quality in Pinios with a process-based model. Simulated abiotic stressor parameters (predictors) were linked to two biotic indicators, the macroinvertebrate indicators ASPT and EPT, with empirical modelling based on boosted regression trees and general linear models. Our results showed that the *techno world* scenario driven by fast economic growth and intensive exploitation of energy resources had the largest impact on both the abiotic status (nutrient loads and concentrations in water) and the biotic indicators. In contrast, the predicted changes under the other two future worlds, *consensus and fragmented*, were more diverse and were mostly dictated by the projected climate. This work showed that the future scenarios, especially the mid-century ones, had significant impact on both abiotic status and biotic responses underpinning the need for implementing catchment management practices able to mitigate the ecological threat on waters in the long-term.

© 2018 Elsevier B.V. All rights reserved.

* Corresponding author.
E-mail address: kstefani@chi.civil.ntua.gr (K. Stefanidis).

https://doi.org/10.1016/j.scitotenv.2018.01.282
0048-9697/© 2018 Elsevier B.V. All rights reserved.

1. Introduction

Mediterranean rivers are under ecological threat by a variety of pressures. Nutrient pollution, habitat fragmentation and alteration in hydrology are some of the most common problems that Mediterranean lotic systems are facing today (Milly et al., 2005; Ormerod et al., 2010; Vörösmarty et al., 2010). Specifically changes in rivers' hydromorphology along with increased nutrient loadings are known to heavily influence both the ecological integrity and the aquatic biodiversity of these systems (Gasith and Resh, 1999; Bonada and Resh, 2013; Hershkovitz and Gasith, 2013). Since most European rivers are affected by multiple stressors operating simultaneously (Ormerod et al., 2010), it is very likely that synergistic or antagonistic interactions among stressors may result in unpredictable outcomes known as "ecological surprises" (Folt et al., 1999; Hale et al., 2017). This became apparent when in many European streams and rivers the hydromorphology and/or water chemistry improved but the ecological status has remained well below the good ecological status.

Climate change is also considered a highly important pressure, especially in Southern Europe, where several studies have indicated severe impacts on rivers and streams (e.g. Liuzzo et al., 2015; Santos et al., 2015; Sellami et al., 2016). What we have learnt so far is that future climatic projections, according to the fifth assessment report of the Intergovernmental Panel on Climate Change — IPCC-5AR (IPCC, 2013), depict changes in global water cycle, with increases in disparity between dry and wet regions. Practically this means that in some areas (from 30°N to 85°N) precipitation over land is expected to increase, while from 10°S to 30°N there are predictions for notable decreases (Grover, 2015). For the Mediterranean region, future projections suggest an increase in aridity that is likely to induce a further reduction in water availability. Alterations of seasonal variability and total amount of precipitation, combined with a simultaneous raise of temperature are expected to have a remarkable impact on water cycle enhancing water scarcity and drought (e.g. Sheffield and Wood, 2008; Mariotti et al., 2008).

Under conditions of multiple stresses any restoration actions may initiate complex cause-effect chains of recovery, which are poorly understood and are not always guaranteed to have the desired outcome (Feld et al., 2011). Therefore, for the Mediterranean rivers in particular, it is crucial to understand deeply how the most common stressor of water scarcity interacts with other stressors (nutrient pollution, climate change) and to communicate this information to managers and policymakers for the adaptation of appropriate management measures that address the combined stressor effect. To ensure the good ecological quality of rivers and streams there is an additional need to be able to predict how the aquatic biota respond to various conditions (Aguiar and Ferreira, 2005; Hooke, 2006). Thus, implementing appropriate mitigation and restoration actions requires understanding both how the biota respond to multiple anthropogenic pressures at present and how biota will be affected by climate change and future anthropogenic activities.

The purpose of this article is to investigate how future scenarios of multiple stressors will affect ecological status and the delivered services of Pinios by implementing an efficient modelling approach that links a number of different abiotic and biotic components of the catchment such as hydrology, nutrients, land use, climate, management practices, ecology and ecosystem services. Our research hypothesis is based on the anticipated impact of climate change on the catchment's hydrology. We expect that projected decrease of precipitation and increase of air temperature will decrease water availability enhancing nutrient pollution and consequently affecting the benthic invertebrate communities. Macroinvertebrates were chosen as the biotic response mainly for two reasons. First, benthic invertebrates are considered an ideal group of organisms for assessing the ecological quality of rivers because of their sensitivity to changes in properties of water quality and aquatic habitat (Bonada et al., 2007; Feld and Hering, 2007; Skoulikidis et al., 2009). Macroinvertebate metrics respond to a wide array of human pressures and as a result they are used in many countries for monitoring the ecological status (Sandin and Hering, 2004; Birk and Hering, 2006). Secondly, macroinvertebrates are the most well studied biotic element in Pinios catchment. Thus, a solid empirical dataset by the Greek Ministry of Environment and previous published studies (Chatzinikolaou, 2007; Chatzinikolaou et al., 2010) is available, enabling us to study the effects of multiple stressors on an important aspect of ecology.

By multiple stressors, we mean changes of environmental factors that occur in concert and affect ecological status, water quality and quantity, and ecosystem services. The implemented modelling scheme was developed within the EU-funded project MARS (Hering et al., 2015) and aims in assessing the multiple stressor effects on biotic and abiotic indicators by linking the outcome of "abiotic" process-based models with the biota and ecosystem services through empirical modelling. Within this context, the implementation of future world scenarios enables us to evaluate different climatic projections and socioeconomic trends, in particular the ones selected for a pan-European implementation in MARS. The objectives of this study are: (i) to quantify the responses of abiotic, biotic and service-related indicators to multiple stressors in Pinios and (ii) to discuss the changes in hydrology, water quality, ecological status and the delivered services within the catchment under the different future scenarios.

2. Methods

2.1. Study area

The Pinios basin covers almost entirely one of the Greek River Basin Districts (RBDs), the RBD of Thessaly in Central Greece (Fig. 1). The basin has high relief in the western and northwestern part, and topography is smoother in the central, southern and southeastern part where the large agricultural valley is developed. The catchment (with an area of approximately 10,600 km^2) is the most important agricultural producer in Greece, with fertile soils but a very dry climate during summer. Usually, the dry periods are accompanied by high temperatures, which lead to higher evapotranspiration rates and dry soils. These conditions inversely affect both the natural vegetation and the agriculture of the region resulting in irrigation cutbacks, overexploitation of groundwater and significant losses of crop yields (Panagopoulos et al., 2014). Water overexploitation in Pinios basin may lead to low river flows (negligible during summer), the drying up of small lakes/reservoirs and low groundwater levels, which make water more expensive to obtain (deep pumping) and enhance saline water intrusion in coastal areas in the eastern part. Therefore, the most important pressure in the Pinios basin is water abstraction for irrigation. Another important environmental issue in the area is surface and groundwater nitrate pollution caused by intensive and sometimes excessive crop fertilization (Psomas et al., 2016). Climate change is also a possible future pressure due to the predicted lower precipitation and higher temperatures, especially within the dry period, when crops are growing.

2.2. Data availability

There are various sources of information and environmental data for Pinios basin such as previous projects, published and unpublished studies as well as the RBMP of the Thessaly RBD, within which, Pinios basin is entirely located. In this study we take advantage of our previous extensive work on collecting and/or deriving the necessary datasets for the basin (Panagopoulos et al., 2013, 2014; Stefanidis et al., 2016).

Precipitation, temperature and other meteorological variables are measured through point stations all across the Pinios basin from the Greek Ministry of Environment and Climate Change & the Public Power Corporation. Precipitation is available from 1975 to 2010. Annual precipitation in Pinios ranges between 390 mm and 1250 mm with an average annual depth of 760 mm and significant seasonal and monthly deviation. Reliable and adequate hydrologic time-series are available

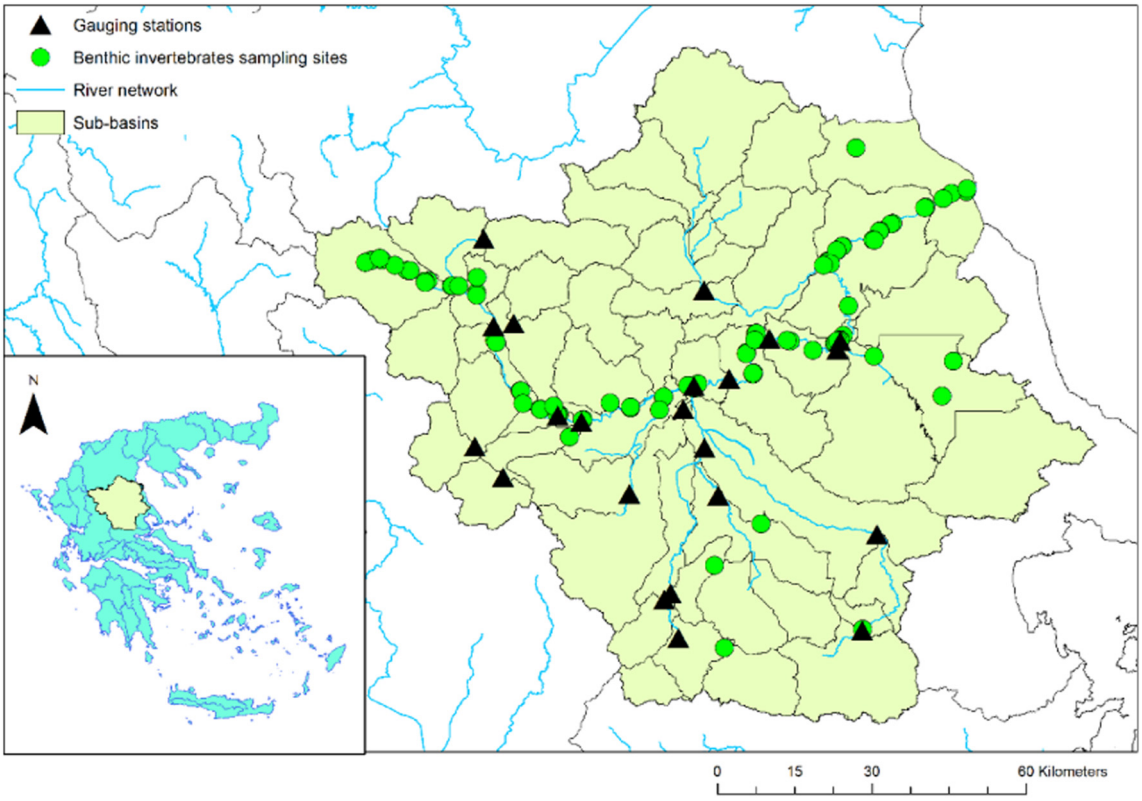


Fig. 1. The Pinios river basin in Central Greece. Key data layers are shown including, sub-basins, as well as, sampling sites and gauging stations.

from two gauged stations located upstream the total outlet of the basin. Systematic measurements of nutrients were also used from two river sites that almost coincide with the hydrologic ones. Aquatic biological data in the catchment mainly concern macroinvertebrates (community data e.g. taxa richness, abundance etc.) comprised by data obtained from two different sources. The first source is based on previously published data collected from 80 sites along the stretch of river Pinios during autumn of 2002 (Chatzinikolaou, 2007; Chatzinikolaou et al., 2010). The second source is the Greek National Monitoring program which provided us with data collected from 30 sites in summer of 2012 and 32 sites in spring of 2013. The merged dataset contains semi-quantitative community information at family level from a total of 142 samples collected from different sites across the catchment of river Pinios (Fig. 1). This dataset also contains physicochemical data of water collected from the same sampling sites such as nutrient concentration in water (phosphate, nitrate, nitrite and ammonium) as well as BOD, surface dissolved oxygen (DO), saturation %, pH, conductivity, total suspended solids (TSS) and water discharge (Stefanidis et al., 2016).

2.3. Process based modelling

For simulating hydrologic and water quality processes, as well as crop productivity in the Pinios basin, the SWAT (Soil and Water Assessment Tool) model is used within a GIS environment (SWAT, 2013). SWAT is a river basin model developed by the United Sates Department of Agriculture (USDA) for use in complex agricultural landscapes and is freely available (http://swatmodel.tamu.edu/). SWAT includes mathematical descriptions of physical, biogeochemical and hydrochemical processes, and combines elements of a physical and conceptual semi-empirical nature (Neitsch et al., 2009). Today, it is considered a robust, interdisciplinary tool, extensively applied in Europe, USA and the rest of the world.

A catchment in the GIS-based SWAT environment is divided into subbasins and subsequently into Hydrologic Response Units (HRUs). The subbasin delineation is particularly beneficial when different areas of the catchment are dominated by land uses and soils dissimilar enough in properties to impact hydrology (SWAT, 2013). HRUs are areas which represent the different combinations of land use and soil types in each subbasin. The processes associated with water and sediment movement, crop growth and nutrient cycling are modeled at the HRU scale. Hydrology is based on the water balance equation in the soil profile, where the processes simulated include surface runoff/infiltration, evapotranspiration, lateral flow, percolation, and return flow. The model considers a shallow unconfined aquifer, which contributes to the return flow and a deep confined aquifer acting as a source or sink.

Agricultural management practices are defined in SWAT by specific management operations (Arabi et al., 2008). Planting, harvesting, tillage passes, irrigation, grazing and nutrient applications can be simulated for each cropping or livestock system with specific dates and management parameters (e.g. tillage depth, N and P contents and amount of fertilizer and manure types, irrigation dates and amounts etc.). The crop growth component of SWAT is capable of simulating a wide range of crop rotation, grassland/pasture systems, and trees. Potential crop growth and yield are usually not achieved as they are inhibited by temperature, water, nitrogen and phosphorus stress factors. To simulate the timing and amount of irrigation water and fertilization applications there are the user specified and the automatic options. In the automatic option, an irrigation event is triggered based on a water-stress threshold, while fertilization based on a nitrogen stress factor (Neitsch et al., 2009).

The present study builds its development on the existing well-constructed Pinios basin model dividing the basin into 49 subbasins (Fig. 1) and 361 Hydrologic Response Units (HRUs), which represent land pieces with unique combinations of land use, management, slope and soil characteristics (Panagopoulos et al., 2013, 2014). The model has been successfully calibrated and validated based on monthly river flows for a long period with available data in two river sites

(Panagopoulos et al., 2013, 2014). As far as water quality calibration is concerned, simulated river loads have been compared with nitrate and phosphorus observations on a seasonal basis (Panagopoulos et al., 2012). A detailed presentation of the model's hydrologic and water quality calibration can be found in Panagopoulos et al. (2012, 2013, 2014).

2.4. Development of empirical modelling and linkages between stressors and indicators

Based on the available macroinvertebrate community data we have calculated several candidate metrics to be used as response variables to nutrient and hydrologic parameters predicted by SWAT (Stefanidis et al., 2016). Specifically, we calculated the BMWP (Biological Monitoring Working Party) and the ASPT (Average Score Per Taxon) score according to the BMWP system (Armitage et al., 1983). Depending on the data availability we calculated additional metrics such as the number of Ephemeroptera, Plecoptera and Trichoptera families (EPT), the relative abundance of Gastropoda, Oligochaeta and Diptera families subtracted from 1 (1-GOLD), the Log transformed abundance of selected families of Ephemeroptera, Plecoptera, Trichoptera and Diptera (Log10(SelEPTD +1)), the total number of taxa, the Shannon diversity index and the species evenness index. Environmental variables were used as stressors (predictors) when building the empirical models. In order to include the effect of natural environmental gradients on the response of biological metrics we used the altitude of the sampling sites as an additional environmental predictor. Summary statistics for the candidate metrics and the environmental parameters are presented in Table 1.

Based on data screening results we selected as best biological indicators the ASPT and EPT metrics. Specifically ASPT was correlated with most of the abiotic variables presenting the strongest linear regressions with nitrates, phosphates and oxygen concentration (Stefanidis et al., 2016). EPT presented stronger linear relationships with discharge and oxygen and weaker linear relationships with DIN and phosphate (Stefanidis et al., 2016). For the biotic/abiotic linkage, boosted regression trees (BRT) and general linear models (GLM) were applied in order to build models that best describe the response of the biotic indicators to abiotic descriptors. All the observed stressor variables from the sample sites were log transformed prior to the analysis and from the 142 samples only the non-missing cases were considered. Collinearity between the variables was assessed with the use of the Variance Inflation Factor (VIF). All parameters exceeding a VIF value greater than eight were excluded from the analysis following a stepwise procedure. BRT modelling was performed with packages gbm and dismo (Elith et al., 2008; Hijmans et al., 2013) for R version 3.2.3 (R Core Team, 2015). The development of BRT was based on the guidelines from Elith et al. (2008). The 'tree complexity' was set to two and the 'learning rate' was adjusted to ensure that, approximately, from 1000 to 1500 trees were combined into the final model. Next, GLMs were developed using as predictors the most high ranking stressor variables as derived from the BRTs. GLMs were run using the Gaussian family. In order to assess the goodness-of-fit for each model the pseudo R-squared was computed. All the analyses were performed with the R version 3.2.3 (R Core Team, 2015).

Table 1
(from Stefanidis et al., 2016). Descriptive statistics for the data used in our analysis.

Variable	Mean	Std. error	Median	Min	Max	N
BMWP score	50.51	2.90	43.00	3	194	142
ASPT	4.65	0.10	4.53	1	7.44	142
EPT	3.84	0.27	3.00	0	11	142
1-GOLD	0.74	0.03	0.86	0.01	1	80
Log_{10}(SelEPTD+1)	0.39	0.07	0.00	0	2.03	80
Number of taxa	10.39	0.47	9.00	1	35	142
Shannon diversity index	1.30	0.07	1.46	0	2.4	80
Evenness index	0.61	0.03	0.67	0	0.97	80
PO4-P (mg/L)	0.093	0.020	0.042	0	2412	142
NH4-N (μg/L)	69.98	9.99	29.71	0	793	120
NO2-N (μg/L)	36.29	4.46	19.06	0	350	128
NO3-N (mg/L)	1.728	0.195	1.158	0	17.082	140
DIN (mg/L)	1.76	0.194	1.157	0	17.167	140
BOD (mg/L)	2.427	0.207	1.85	0.11	6.79	80
DO (mg/L)	8.41	0.18	8.63	1.64	14.39	142
Saturation (%)	89.89	2.06	91.3	17.7	191	142
Water temperature	18.68	0.38	18.5	8.3	34.2	142
pH	7.9	0.04	7.94	6.27	9.47	142
Conductivity (mS/cm)	0.53	0.03	0.48	0.22	5.01	142
TSS (mg/L)	268.93	18.16	239.67	110.00	2656.00	142
Discharge (m^3/s)	3.28	0.28	2.42	0.01	8.68	102

2.5. Ecosystem services in Pinios

The main ecosystem services in the Pinios basin are the provision of irrigation water, and crop products. Secondary services are the industrial water use, aquacultures, recreational activity, mining and livestock activities but are not addressed in the study. The main ecosystem services which are identified and highlighted in the RBM Plan are mostly related to water use services and specifically provision of drinking and irrigation water. In this paper we present agricultural yields (cotton and corn) and the abstracted water used for irrigation under the different scenarios.

2.6. Scenarios development

In order to assess the potential impacts of future world scenarios on the water status and ecosystem services of Pinios basin, we applied three future worlds of the EU funded MARS project (Hering et al., 2015; http://mars-project.eu/) representing combinations of Representative Concentration Pathways (RCPs) and Shared Socioeconomic pathways (SSPs) (Kriegler et al., 2012; O'Neill et al., 2014).

The RCPs refer to radiative forcing pathways that describe an emission trajectory and concentration by the year 2100 (Van Vuuren et al., 2011). There are four radiative forcing scenarios and are defined depending on the total radiative forcing in year 2100 relative to 1750 (Table 2). RCP 2.6 is a mitigation scenario with emissions that peak and decline before 2100. RCPs 4.5 and 6.0 are stabilization scenarios and RCP 8.5 is a rising scenario with very high greenhouse gas emissions. These four RCPs are based on previous available in the literature scenarios, and they were built on specific socioeconomic assumptions. The SSPs are defined as 'reference pathways' describing plausible alternative trends in the evolution of society and ecosystems. Five SSPs have been defined that provide a starting point for different narratives depending on the response of the society to climate change (O'Neill et al., 2014).

In this work we used projected surface air temperature and precipitation produced by two climate models, GFDL-ESM2M and IPSL-CM5A-LR, after applying bias correction with linear scaling. Regarding SSPs, we used the SSP2 which refers to a *techno world* driven by a fast economic development, the SSP5 which refers to a *consensus world*, with economy and population growing in the same pace as now and the SSP3, which refers to the *fragmented world* where each region fights for its own survival.

For the detailed representation of each of the SSPs we chose management options that fit in their future socio-economic narratives. In particular, for the fast growing economy of the *techno world*, the representation in SWAT included a precision irrigation method for the irrigated crops of Pinios assuming that methods and equipment are substantially upgraded and an expansion of the irrigated areas by 40% (covering fallow areas) for growing more corn for biofuel production. This practically resulted to an increase of the irrigated area by 80,000 ha rising the total irrigated land to 280,000 ha to serve energy demands. Fallow areas in the baseline were located among the crop areas all across the catchment and such a severe corn increase is expected to

Table 2
Representative concentration pathways in the year 2100 (source Van Vuuren et al., 2011).

	Radiative forcing	CO2 equivalent concentration	Rate of change of radiative forcing
RCP 8.5	8.5 W/m2	1350 ppm	Rising
RCP 6.0	6.0 W/m2	850 ppm	Stabilizing
RCP 4.5	4.5 W/m2	650 ppm	Stabilizing
RCP 2.6	2.6 W/m2	450 ppm	Declining

result in a significant water abstraction increase in areas with high water availability but to a low or negligible water exploitation increase in stressed areas with limited water resources. A third management change in the basin under the *techno world* was the 20% fertilization increase to all crops, which serves as an additional practice towards the maximization of profit.

In the *consensus world* on the other hand, we decided not to change at all crop patterns and irrigation water amounts and scheduling in the basin, hence, the respective simulations were driven only from climate change (two models). Finally, the *fragmented world* was represented by a combined 20% increase in both the irrigation and fertilization amounts applied to the cropping systems of the baseline in an effort to 'mimic' Pinios farmers' efforts to fight for their survival without considering much the environment. The combination of the management options with the specific climate conditions as derived by the climate scenarios resulted in 12 model runs (2 climate models × 3 storylines × 2 10-y periods). The results are reported for three different time periods. One centered around the middle year 2000 of the historical period 1995–2005, one centered around 2030 (2025–2035) and one around 2060 (2055–2065). The year 2030 is a WFD target-year (Directive 2000/60/EC, 2000), while 2060 is a far future year of interest. The total number of runs was 13 including the baseline (Table 3).

It should be noted here that water abstractions in our model occur under a number of restrictions related to groundwater and reservoir availability, which preserve water resources sustainability. For example, we have set very small initial depths of water in the shallow aquifers and reservoirs in order for the model to always need aquifer and reservoir water replenishment during the wet period of the hydrologic year (Oct–April) to be able to extract and apply water to crops during the following dry period. Also, minimum required flows downstream the reservoirs have been defined in our model. Therefore, due to these plausible restrictions the amount of water abstracted for irrigation does not always meet the maximum theoretical doses of the irrigation scheduling. In this way, sustainability of water bodies is ensured throughout the simulation period as the irrigated water applied is the water that has naturally enriched water sources. In other words, only renewable water resources are used, thus, the irrigation water applied represents the guaranteed ecosystem service that the hydrologic system can deliver under each scenario. Additionally, the total abstracted water includes a fraction of water that is lost during its distribution to crops; thus, the water that is not used by the crop itself but which should always be considered in the calculations. Finally, available but not used water resources (groundwater) always exist across the entire basin, in the natural subbasins with small or negligible agricultural activities. However, it is not realistic to transfer these quantities in remote subbasins for use by crops. Therefore, in our model these water quantities are not practically considered as available water resources.

Table 3
Detailed presentation of scenario model runs performed for the Pinios basin.

Scenarios	Climate model	Period
Baseline		1995–2005
Techno world	GFDL-ESM2M	2025–2035
This is a world driven by economy. A fast economic		2055–2065
development increases the use of energy. Policies are	IPSL-CMA-LR	2025–2035
not focused on the environment but on enhancing		2055–2065
trade and benefitting the economic growth. Climate		
is changing rapidly. This world is based on a		
combination of SSP5 and climate scenario 8.5.		
Consensus world	GFDL-ESM2M	2025–2035
Economy and population grow at the same pace as		2055–2065
now. Policies to protect the environment are	IPSL-CMA-LR	2025–2035
continued after 2020, and the preservation of nature		2055–2065
is regulated by the government. This world is based		
on a combination of SSP2 and climate scenario 4.5.		
Fragmented world	GFDL-ESM2M	2025–2035
This world is characterized by an unequal		2055–2065
development of the different countries. International	IPSL-CMA-LR	2025–2035
trade agreements are stopped and each country		2055–2065
needs to fight for its own survival. Environment is		
just protected by rich countries at a local scale, but in		
general no attention is paid to the preservation of		
nature. This world is based on a combination of SSP3		
and climate scenario 8.5.		

3. Results and discussion

3.1. Changes in abiotic state

Table 4 summarizes the mean annual precipitation depths and temperatures and the mean annual SWAT predictions related to hydrology, water quality and crop productivity in Pinios basin, for the baseline conditions and for all scenarios tested.

Clearly, the numbers in the temperature column of Table 4 show first that there is a general warming in Pinios. Mean annual temperatures increase under all scenarios with the differences from the baseline being higher in the RCP 8.5-driven *techno* and *fragmented worlds*, especially in mid-century (2060), when the IPSL climate model predicts an almost 4 °C increase. The first column with numeric results in Table 4 also shows that all the climate model runs predicted an increase of total precipitation in 2030 and a decrease following in 2060, with an exception for the *consensus world*, which is developed under RCP 4.5 (see Table 4). The average annual precipitation simulated for the baseline period 1995–2005 is approximately 700 mm while the highest average annual precipitation is estimated for the *consensus world* scenario run (>800 mm) in 2030. The smallest precipitation is predicted for both the *techno* and the *fragmented worlds* (same RCP - RCP8.5) around 650 mm for the year 2060, which is less than a 10% decrease from the baseline. Generally, it appears that the most optimistic RCP 4.5 scenarios predict higher precipitations.

The precipitation results, especially for the early century (2030), at first appear as a paradox as there are several studies that have shown a general trend of intensification of aridity in the Mediterranean region due to decrease of precipitation and rise of temperature. For example, Mimikou and Baltas (2013) have highlighted a predicted decrease of precipitation and runoff in four large river basins in Greece by 2020 and 2050 based on various future climate scenarios. Similarly, Papadaki et al. (2016) showed that A1B (2021–2050, 2071–2100) and A2 (2071–2100) climate scenarios, based on CMIP3 (Coupled Model Intercomparison Project Phase 3) models, predicted a decrease of rainfall that along with an increment in temperature were responsible for decreased stream flows in two mountainous Mediterranean catchments. Indeed, studies that have employed CMIP3 scenarios, such as A1B and A2, have shown a remarkable decrease of precipitation in some areas of Greece, up to 60% by the end of the century (Paparrizos et al., 2016; Tolika et al., 2012). However, there are few studies based on the more

Table 4
Numeric results from the implementation of scenarios with SWAT in the Pinios river basin.

	Scenarios	PCP mm	IRR water hm^3	Runoff mm	Av T °C	Sed t/ha	TN kg/ha	TP kg/ha	COT t/ha	CORN t/ha	COT 1000 t/y	CORN 1000 t/y
Baseline		692	547	235	15.2	1.31	9.2	0.29	2.38	11.38	390	261
Techno world	GFDL-2030	746	739	249	15.9	0.65	11.5	0.17	2.39	10.71	392	1145
RCP8.5	IPSL-2030	775	650	282	17.0	2.55	14.6	0.39	2.06	9.52	338	1018
	GFDL-2060	633	729	175	16.9	0.60	7.9	0.13	2.15	10.21	352	1092
	IPSL-2060	651	638	186	18.9	2.74	8.2	0.28	1.62	8.38	265	896
Consensus world	GFDL-2030	824	639	334	15.8	1.47	13.3	0.24	2.69	11.74	441	269
RCP4.5	IPSL-2030	797	581	320	16.3	0.97	12.9	0.25	2.29	10.39	375	238
	GFDL-2060	780	634	275	15.7	1.02	9.7	0.22	2.61	11.51	428	264
	IPSL-2060	694	511	210	17.3	3.04	7.7	0.29	1.96	9.93	321	227
Fragmented world	GFDL-2030	741	631	254	15.9	0.56	11.5	0.15	2.49	11.62	408	266
RCP8.5	IPSL-2030	769	539	285	17.0	2.40	14.4	0.34	2.15	10.21	352	234
	GFDL-2060	629	646	179	16.9	0.57	8.0	0.11	2.22	11.16	365	256
	IPSL-2060	646	535	189	18.9	2.62	8.4	0.24	1.66	9.66	273	221

Note: PCP is the annual precipitation in mm, IRR water is the water abstracted annually for irrigation across the Pinios basin in million m^3, Runoff is the total annual runoff of the basin in mm, Av T is the average annual temperature in °C, Sed is the annual erosion rate of the basin in t/ha, TN and TP are the annual Total Nitrogen and Total Phosphorus losses from land to waters in kg/ha and COT and CORN are the annual yields of the two main crops in the basin, cotton and corn, given both as t/ha covered by each crop and as thousands of t per year (1000 t/y) produced in the entire basin.

recent CMIP5 models that predict intensification of heavy rainfall events during winter and in some cases an increase of the annual precipitation. For example in an article of Scoccimarro et al. (2016) it was shown that under RCP 8.5 scenario, CMIP5 models project an increase of heavy precipitation during winter in South Europe (including regions of Mediterranean) by the end of the 21st century, while during summer the duration and the intensity of rainfall events are expected to decrease. Other studies that use CMIP5 models have also predicted an increase of annual precipitation even in arid areas like Sudan (Basheer et al., 2016).

Furthermore, by examining the monthly variation of precipitation in our study (not shown here), we notice a consistent increase in September and October for all climate model runs. However, all runs predicted lower precipitation during the warmest months (May–August), with the highest reductions from the baseline occurring in July and August. Thus, the climate scenarios predict an increase of precipitation, mostly during autumn, but negative changes for the two warmest and most water demanding summer months. Therefore, even the scenarios where precipitation annual depths increase from the baseline, predict that the limited water availability of the dry period will deteriorate.

Table 4 also shows the simulated annual runoff in Pinios basin, as well as sediment and nutrient losses from land to waters, occurring on an annual basis. As mentioned previously, all scenarios predicted an increase of annual precipitation in Pinios for the period 2025–2035, which is responsible for the observed increase in annual runoff compared to the baseline. However, the situation is different for the period 2055–2065 when the model mostly predicted a decrease of total runoff following the decreased precipitation.

The runoff predictions made for the 2060 by RCP 8.5 scenarios appear to concur with findings from previous studies in the area (Mimikou et al., 2000; Mimikou and Baltas, 2013) that highlight a decrease of mean annual precipitation and runoff in the studied area up to 14.1% and 18.4% respectively by 2050. The *techno world* scenario in particular predicts a decrease in annual precipitation and runoff by 8.5% and 25% respectively compared to the baseline conditions.

Regardless the scenario, the runs have suggested that intra-annual variability in the hydrology of the catchment is expected to change considerably, as we have observed mean monthly runoff changes similar to the ones of precipitation (increase in autumn, reduction in summer months). These results agree with findings from other studies that have highlighted the role of climate change in altering daily, seasonal and inter-annual trends of catchment runoff (Dudula and Randhir, 2016).

Changes in hydrology will affect sediments, N and P losses within the catchment. Simulated sediments and P in SWAT are strongly related to surface runoff while N to subsurface runoff (Neitsch et al., 2009). This means that under a climate with a large number of precipitation extremes, surface runoff and subsequently sediment and P losses are enhanced, while total runoff's magnitude mostly enhances loss of soluble forms of nutrients such as nitrates. The results in Table 4 clearly show that climate is the major driver of pollutant losses. First, we observe that the IPSL-CM5A-LR climate model increases simulated annual sediment losses, obviously due to increased precipitation extremes, which are even more frequent farer in the future (2060), regardless of the total annual precipitation depth. The intensification of agricultural activities of both the *techno* and *fragmented worlds* does not seem as responsible as their common climate (RCP 8.5) for the changes in sediment loads. This is proved by the *fragmented world* sediment results, when slight management changes were occurring but sediment rates were almost as high as in the *techno world* scenario.

Similarly, climate and specifically the projected increased total precipitation of both the GFDL and IPSL models for 2030 resulted in increased total runoff amounts causing higher N water pollution. Decreased precipitation and runoff in 2060 resulted in lower N losses accordingly. The role of agricultural management cannot be clearly indicated. Although total N fertilization increases in the catchment in the *techno* and *fragmented worlds*, N loss deviations from the baseline seem to occur mostly according to the changes in climate. These findings indicate that climate alone is the main driver of changes in N pollution in the basin. Similar results were observed in a study of Shrestha et al. (2017), where it was shown that TN and TP losses declined by 24.3 and 29% respectively under a RCP 8.5 climate scenario in a Mediterranean catchment in South Australia for the future period 2046–2070. This decline was attributed to a decrease of runoff due to the projected precipitation decrease. Other studies on climate change effects have also shown that nitrate losses are governed by the magnitude of runoff (Panagopoulos et al., 2011; Molina-Navarro et al., 2014). Conversely, TP losses did not follow the runoff variation. For example when runoff increased under the *consensus world*, TP losses declined. This observation agrees with previous studies where P transport was related to sediment loads and lateral flows, suggesting that soil erosion is one of the main sources of TP in the catchment (Zheng et al., 2004; Panagopoulos et al., 2011; Molina-Navarro et al., 2014).

Figs. 2 and 3 show the spatial variation of nitrate and total P annual concentrations in water across 47 sub-basins of the Pinios catchment under all scenarios. Practically, these maps take into consideration changes in both runoff and nutrient losses aiding us to identify areas with the highest nutrient impact on aquatic life. One of the most important conclusions that can be drawn from these maps is the predicted increase of nitrate concentrations compared to the baseline conditions for all the scenarios and for both future periods. Specifically, we can note a large increase of nitrate concentrations in several subbasins for the

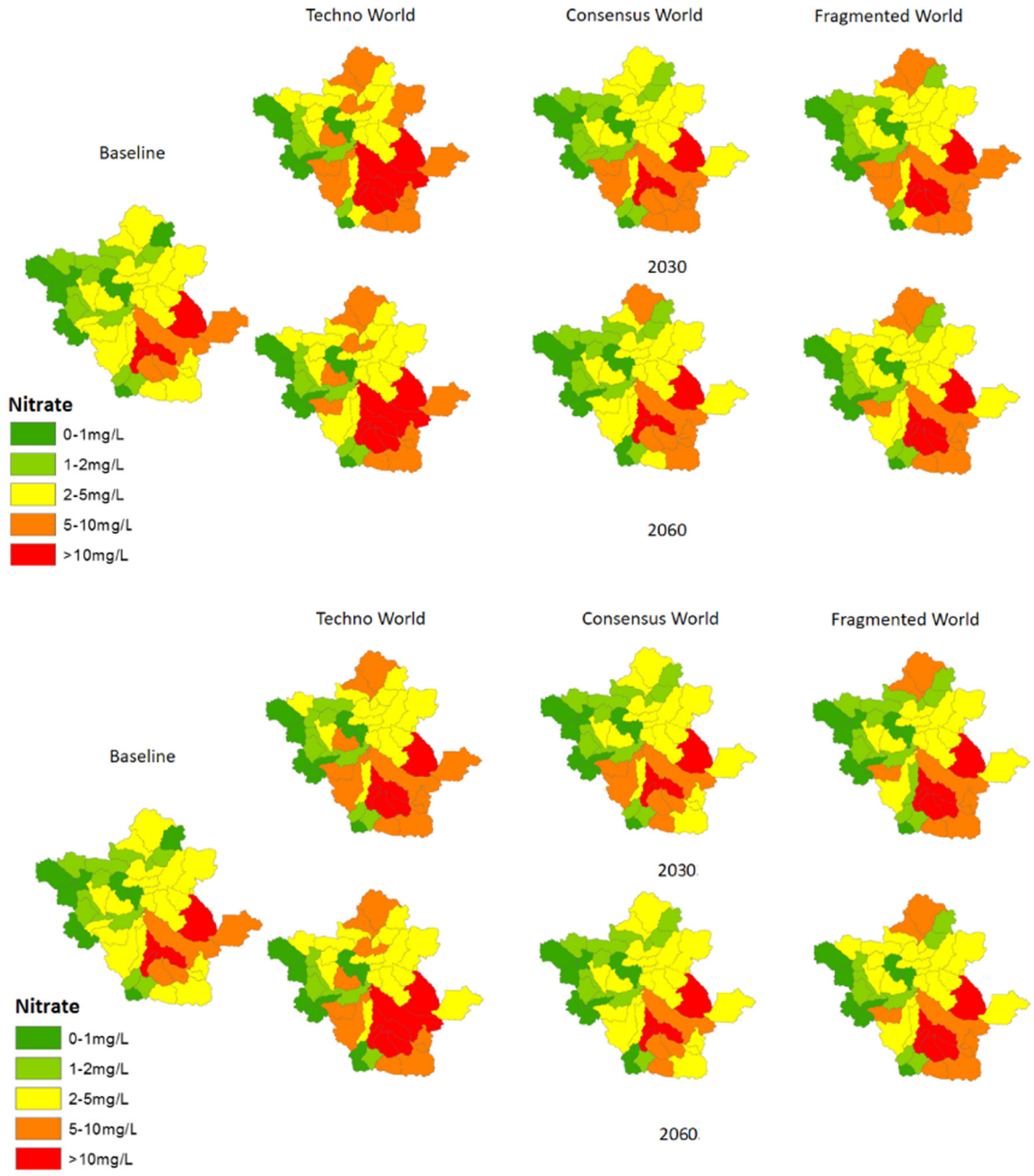


Fig. 2. Maps showing average nitrate concentration in water for the baseline period (1995–2005) and the three future scenarios (2030 and 2060) in the Pinios basin. Top graph shows predictions based on climate model GFDL-ESM2M and bottom graph based on IPSL-CM5A-LR.

techno world scenario for both reporting periods. The increase appears to be in some occasions higher when climate projections based on the GFDL-ESM2M model are considered. In contrast, the highest total P concentrations are predicted for the *techno world* scenario based on the IPSL-CM5A-LR model and for the 2060 time period. Another notable finding is that the *consensus* world scenario appears to affect less the nitrate and P concentrations in water and in few subbasins we can even observe an improvement regardless of the time period.

3.2. Changes in agricultural yields and ecosystem services

Table 4 lists also the predicted annual average cotton and corn yields in thousands tones per year and the actual water abstractions from the basin occurring on a mean annual basis under all scenarios.

Our findings showed that the *techno world* can increase substantially the production of corn due to the significant increase of corn areas for biofuel production (from ~20,000 ha to ~100,000 ha in our model). Increased water availability of the climate models in 2030 seems to have sometimes a positive effect on yields for both cotton and corn. However, IPSL always results in reduced yields and smaller water abstractions than the GFDL does. As was discussed previously, IPSL is characterized by a more intense temporal variability of rainfall with the enhancement of extreme events. This generally decreases water storage in the basin compared to the GFDL model, causing less water availability, water abstraction (see Table 4) and subsequent crop water use. Additionally, the reduced cotton and corn yields of the IPSL scenarios compared to the respective GFDL ones can also be attributed to the greater nutrient losses from land to surface waters (or lower nutrient availability in soil). However, compared to the baseline, the total water abstracted with the IPSL

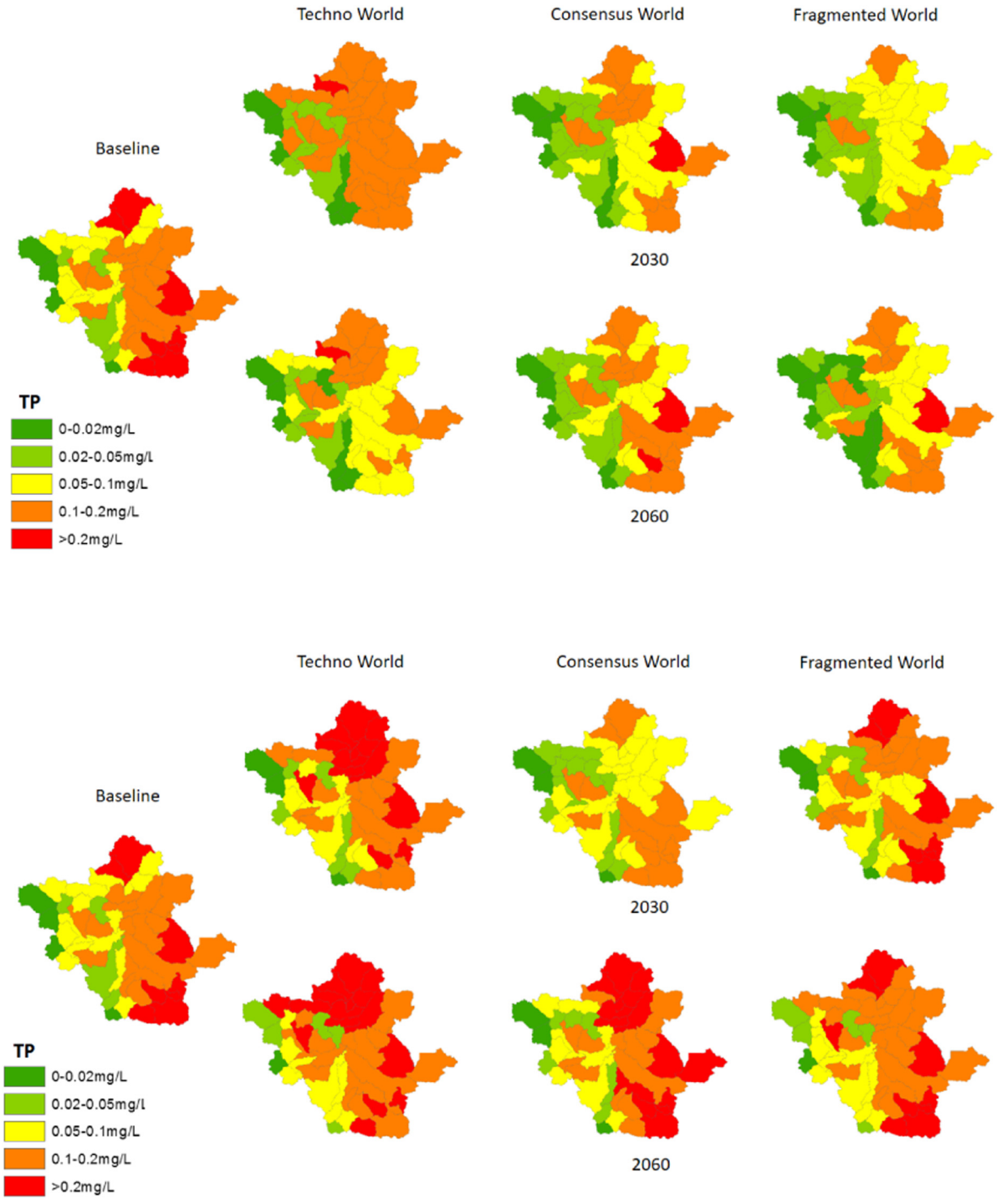


Fig. 3. Maps showing average total phosphorus (TP) concentration in water for the baseline period (1995–2005) and the three future scenarios (2030 and 2060) in the Pinios basin. Top graph shows predictions based on climate model GFDL-ESM2M and bottom graph based on IPSL-CM5A-LR.

model is practically never lower than the baseline. Furthermore, in a previous work we showed that management options, such as deficit irrigation and precision agriculture, although reduced significantly the abstracted water, were found to have a small impact on changing surface runoff and river flows. For example, an extended implementation of deficit irrigation by 30% led to very small and non-significant increase of the mean annual flow of Pinios river by only 0.38 m^3/s, which is an increase of <0.5% (Stefanidis et al., 2016). This implies that water abstraction has a very small effect on the river flows, especially when compared to the effect driven by the climate change.

3.3. Changes in biotic state

Table 5 provides information on the final models that were used for predicting ASPT and EPT metrics under future scenarios. In regard to the BRTs, the best model for ASPT uses as predictors: dissolved oxygen (DO), nitrate and phosphate concentrations, discharge and altitude. For the EPT the model that was developed is based on DO, water temperature, phosphate and altitude. The ASPT presents a clear positive response to increased DO content and altitude gradient while it relates negatively with nitrate and phosphate concentrations. These

Table 5
Key details of boosted regression trees and general linear models developed using Average Score Per Taxon (ASPT) and number of Ephemeroptera, Plecoptera and Trichoptera families (EPT) as response.

Boosted regression trees			General linear models				
Response	Average Score Per Taxon	No of Ephemeroptera Plecoptera Trichoptera families	Response	Average Score Per Taxon		No of Ephemeroptera Plecoptera Trichoptera families	
Predictor	Relative influence		Predictor	Coefficient	Sig.	Coefficient	Sig.
Altitude	*36.42*	*39.92*	Dissolved oxygen	3.62	$p = 0.012$	15.663	$p < 0.001$
Dissolved oxygen	*18.79*	*22.53*	Altitude	0.002	$p = 0.015$	0.009	$p < 0.001$
Water temperature	–	*11.56*	Temperature	2.79	$p = 0.092$	7.834	$p = 0.019$
Nitrate	*11.80*	–	Nitrate	−0.16	$p = 0.149$	0.41	$p = 0.056$
Phosphate	*8.78*	*7.08*	Phosphate	−0.27	$p = 0.154$		
Discharge	*8.42*	–	Intercept	−1.85	$p = 0.49$	−24.24	$p < 0.001$
Mean total deviance	1.567	9.581	Null deviance	145.713		891.03	
Mean residual deviance	*0.708*	*2.993*	Residual	89.54		411.69	
R^2	*0.55*	*0.69*	R^2	0.39		0.54	
Training data correlation	*0.766*	*0.841*					
CV correlation	*0.544*	*0.722*					

relationships clearly reflect the ability of ASPT to respond to organic pollution (e.g. anoxic conditions). EPT relates positively with altitude, nitrate, water temperature and DO. The positive response to DO and altitude is related with the occurrence of these macroinvertebrate families in good water quality conditions, whereas the positive relation with temperature and nitrate possibly indicates a seasonal effect on the total species richness that affects the EPT number as well. These findings imply an important effect of nutrient pollution, mainly nitrogen, on the occurrence of sensitive in pollution taxa and agree with results from other studies performed elsewhere in Europe and the rest of the world (Johnson and Hering, 2009; Dahm et al., 2013; Lakew and Moog, 2015; Villeneuve et al., 2015). In addition, the significance of oxygen as a key factor for benthic invertebrates has been documented in numerous studies and is closely related to increased decomposition of organic matter triggered by nutrient excess and increasing algal and microbial growth (Johnson and Hering, 2009; Dahm et al., 2013). Discharge was not a significant predictor for ASPT and EPT according to the GLMs. This can be possibly attributed to the fact that indirect effects of stream flow on macroinvertebrate communities are rather connected to impacts on the channel morphology and the habitat heterogeneity (Cortes et al., 2002; Graeber et al., 2013; Waddle and Holmquist, 2013). Instead, other macroinvertebrate indices, such as the Lotic Invertebrate index for Flow Evaluation (LIFE), are known to respond better to changes in flow and channel morphology (Dunbar et al., 2010; Buffagni et al., 2010).

Based on the empirical models we predicted the response of ASPT and EPT metrics at each subbasin using as predictors the mean annual values of the output variables simulated by SWAT. Figs. 4 and 5 show the medians for ASPT and EPT metrics for the whole basin calculated based on predictions made by the GLMs at sub-basin level. Those ASPT

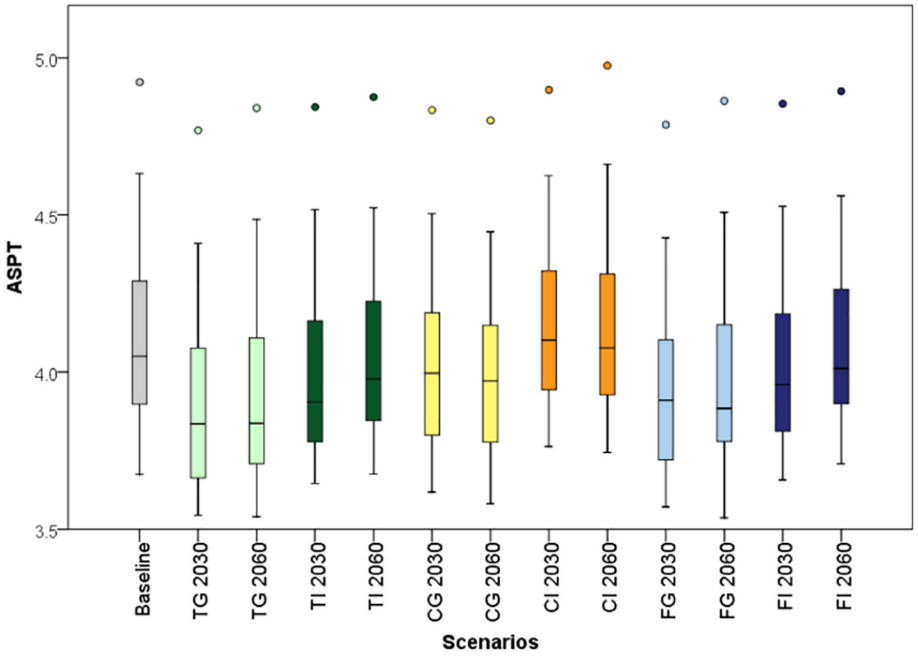


Fig. 4. Median Average Score Per Taxon and 95% confidence levels calculated based on predicted values at each subbasin for the baseline conditions and for each scenario run. Predictions were made with the use of GLMs (T stands for "Techno", C for "Consensus", F for "Fragmented", G for climate model GFDL-ESM2M and I for IPSL-CM5A-LR).

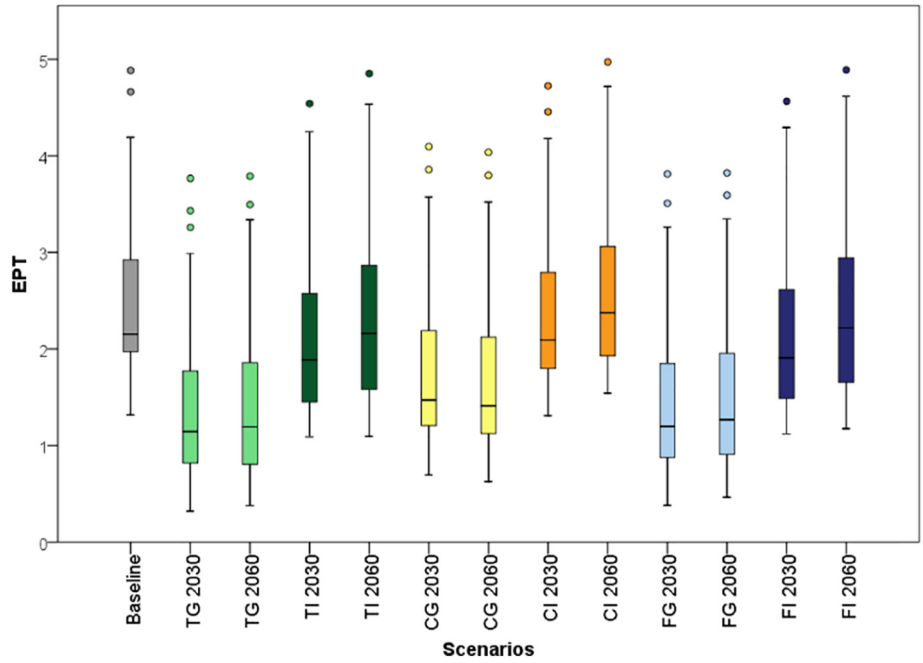


Fig. 5. Median number of Ephemeroptera, Plecoptera, Trichoptera families and 95% confidence levels calculated based on predicted values at each subbasin for the baseline conditions and for each scenario run. Predictions were made with the use of GLMs (T stands for 'Techno', C for 'Consensus', F for 'Fragmented', G for climate model GFDL-ESM2M and I for IPSL-CM5A-LR).

and EPT predictions, averaged within each time period, are presented for all subbasins in Figs. 6 and 7 respectively, showing the spatial variation of the two biotic metrics in Pinios basin.

In regard to the ASPT predicted by the GLM for the baseline conditions, we note that the overall mean for the whole basin is noticeably lower (4.11 vs 4.65) than the average ASPT calculated by real data collected by Chatzinikolaou (2007). The mean ASPT predicted by the BRT is 4.38, still lower than the average obtained by real data but slightly higher than the one predicted by the GLM. This difference between simulated and measured values is explained by the fact that field samplings were carried out in sites with very low anthropogenic pressure that were characterized by high ASPT and EPT values, indicating a good ecological status. Nevertheless, under the baseline conditions our modelling approach resulted in realistic values that are representative of a wide range of nutrient concentrations, which also reflect the effect of agricultural activities in the area. Similar conclusions can be made for the predictions of the EPT compared to the measurements made by Chatzinikolaou (2007).

As far as the scenario results are concerned, the graphs clearly show that all the scenarios based on the GFDL climate model correspond to a decrease for both the ASPT and EPT predicted by the GLMs, with the sharpest decrease observed for the *techno world* scenario results centered around 2030. Regarding the scenario runs based on the IPSL climate model we can note that the results are similar except the *consensus world* future years (2030 and 2060). Similarly, we observed a slight increase for the EPT metric only for the 2055–2065 period. For all the other cases there is a slight decrease in both ASPT and EPT metrics compared with the values for the baseline conditions. From Figs. 6 and 7 we can observe the spatial variation of these changes and particularly we can note the predicted decrease of ASPT and EPT values for most of the subbasins under the *techno* and *fragmented world* scenarios. Studies that assessed the ecological status of streams and rivers across Europe using the ASPT metric have showed that the boundaries between the ecological classes can be rather small (Sandin and Hering, 2004; Birk and Hering, 2006). For example, from a pan-European study made by Sandin and Hering (2004) the difference in class boundaries between high/good and good/moderate status was as low as 0.21 and 0.345 depending on the type of the stream. This practically means that a predicted decrease of ASPT by 0.3–0.5 reflects to a significant impact on the ecological status. Based on our results we can conclude that under the *techno world* scenario is more likely for streams within the Pinios catchment to fail achieving the WFD's objective of "good" ecological status.

These results can be related to the predictions made for the TN as in some occasions the variability of the mean ASPT and EPT among the scenarios agrees with the variability of the TN loads. The standard decrease of N in 2060 compared to 2030 of each scenario is consistent with a similar increase trend for ASPT as we move to the future. Moreover, the highest TN loads and the lowest ASPT average are both predicted for the *techno world* IPSL scenario for the period centered around 2030. However, for cases where the predicted change in nutrients is small, the oxygen concentration appears to be the key factor for the changes in the biotic response. In general, SWAT predicted for all scenarios a decrease of the average concentration of DO, due to the increase of the major associated parameter, the water temperature. The key role of DO in determining the response of ASPT is more obvious in the cases where, although a decrease of nutrient (both N and P) loadings was predicted by SWAT, the biotic metrics did not respond accordingly. Specifically, the *techno* and *fragmented world* scenarios based on both GFDL and IPSL climate models predict a reduction of both nitrate and phosphate loads for the future period 2055–2065 resulting in a "positive" effect on the biotic response (increase of biotic indices). However, because of the oxygen reduction, a decrease of ASPT is still observed under these scenarios. In other words, the oxygen factor has the strongest effect among the stressors, as also shown from the details of the model. On the other hand, under the *consensus world* scenario based on the IPSL climate model there is an increase of the ASPT metric because the predicted change in oxygen concentration is very small and is not able to "counteract" the 'positive' effects of the nutrient loading reduction.

Nevertheless, the results of this work have shown that future climate will affect significantly the benthic invertebrates in the studied area. There are other published studies as well that have underlined the adverse effects of climate change on stream macroinvertebrate communities, but most of these studies have focused on biodiversity changes and specific taxa responses (Domisch et al., 2013; Kuemmerlen et al., 2015; Soria et al., 2017). For example Domisch et al. (2013) and Kuemmerlen et al. (2015) suggested that due to climate change, warm-adapted

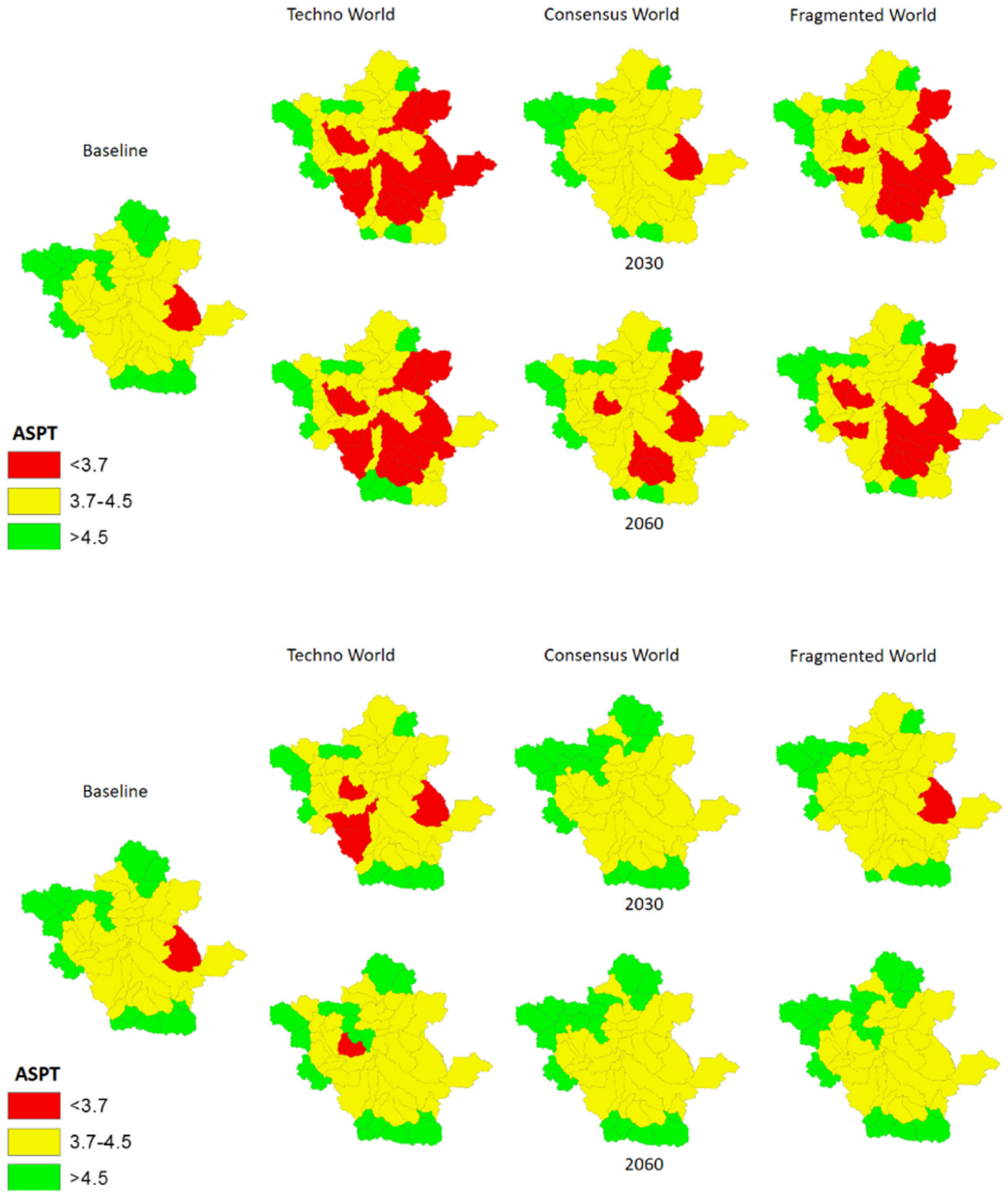


Fig. 6. Maps showing average for Average Score Per Taxon metric for the baseline period (1995–2005) and the three future scenarios (2030 and 2060) in the Pinios basin. The top graph shows predictions based on the climate model GFDL-ESM2M and the bottom graph based on the IPSL-CM5A-LR.

generalist species with high dispersal are likely to replace cold-adapted species with subsequent effects in species composition and diversity. Conversely, our study focuses on predicting changes of ecological status by estimating the response of sensitive to nutrient and organic pollution metrics to future scenarios. From this perspective, our results showed that for the majority of tested scenarios ecological status is expected to downgrade, with the most adverse response anticipated under a world driven by fast economic development with policies that ignore environmental sustainability.

4. Conclusions

All future scenarios tested in this study show an increase of total precipitation in 2030 and a decrease following in 2060 compared to the present. The simulated runoff follows consistently the precipitation pattern. Temperatures increase under all scenarios with the differences from the baseline being higher for 2060. A sharp precipitation increase occurs in the first months of autumn for all the climate model runs. However, all the simulated runs predict lower precipitation during the most water demanding summer months, especially August, in comparison to the baseline conditions.

Based on our results it seems that the climate effect prevail over any other effect generated by the management options that could have an

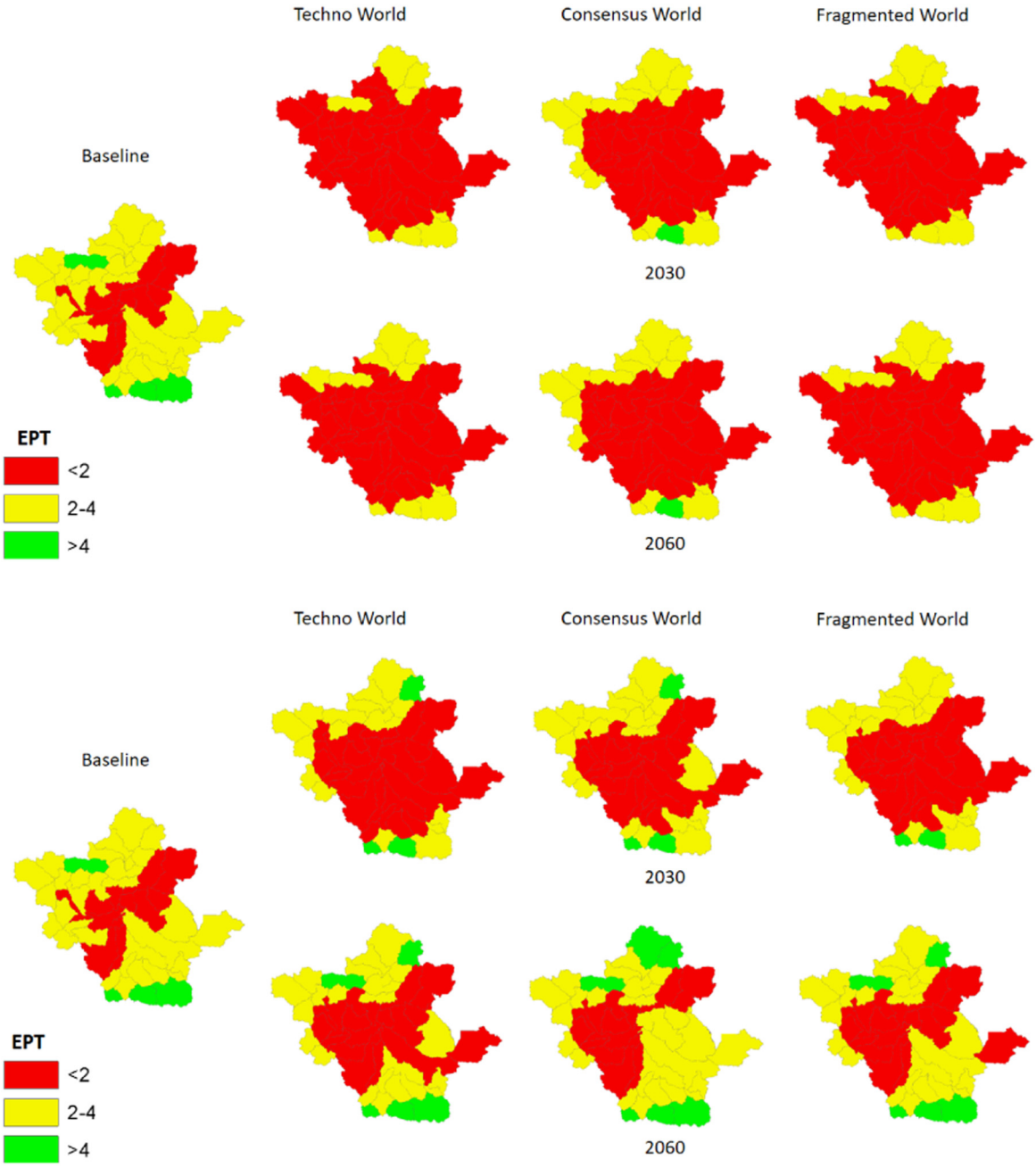


Fig. 7. Maps showing average for number of Ephemera, Plecoptera and Trechoptera families metric for the baseline period (1995–2005) and the three future scenarios (2030 and 2060) in the Pinios basin. The top graph shows predictions based on the climate model GFDL-ESM2M and the bottom graph based on the IPSL-CM5A-LR.

impact on the flow regime of the catchment. Climate is the major driver of nitrogen and phosphorus losses, with agricultural management changes having a secondary role at the large, catchment scale. Apparently, when runoff increases due to precipitation, N losses will also increase (2030) and vice versa (2060). In addition, sediments and P annual losses follow the seasonal variation of hydrology, influenced by the extremeness of events; thus, they are getting clearly higher under the scenarios with the IPSL climate model. Consistently, under all scenarios tested, the requirements for delivered Ecosystem Services to humans are satisfied or in the worst situation, they are very slightly disturbed from the baseline. In the *techno world* in particular, the production of corn is substantially increased due to the significant increase of corn areas for biofuel production.

Increased water availability of the climate models in 2030 has most of the times a positive effect on yields for both cotton and corn. However, IPSL always results in reduced yields and smaller water abstractions than the GFDL does due to the more intense temporal climate variability that reduces water availability and the remaining nutrients in the topsoil for potential use by crops.

Regarding the ecological responses, our findings showed that DO and nutrients are key predictors of both the biotic ASPT and EPT metrics. The effect of oxygen is stronger though, as even under scenarios where nutrients decrease, the biotic metrics still decline due to reduction of oxygen concentration mostly caused by the rise of water temperature. The scenarios based on IPSL climate models are more optimistic in regard to their effects on the biotic indicators, resulting in smaller reductions of the biotic indices in comparison to the predictions based on GFDL models. The biggest negative impact (reduction) on both ASPT and EPT is predicted under the *techno world* scenario and for the future period 2025–2035. The magnitude of the predicted change implies that in

certain subbasins ecological status is likely to downgrade (i.e. from good to moderate status).

It should be noted however that the scenario results and subsequent conclusions presented herein are subject to a certain degree of uncertainty that mainly arises from the climate model data and the simulations produced by the SWAT model. Local topography and special climate conditions might have not been accurately considered by the GCMs. Nevertheless, what we can claim with certainty is that at the large, catchment scale, the hydrologic and water quality changes should be attributed mostly to climate and that management options have only a secondary role in the overall scenarios effect on the river's ecology and delivered ecosystem services (actually in the *consensus world* no management changes were defined to our model). Our catchment scale findings presented in this paper can contribute to a better understanding of the possible future ecology and water quality of the Pinios catchment. Overall, this work can aid water managers to take into consideration future changes in the river basin management planning.

Acknowledgements

This work was supported by the MARS project (Managing Aquatic ecosystems and water Resources under multiple Stress) funded under the 7th EU Framework Programme, Theme 6 (Environment including Climate Change), Contract No: 603378 (http://www.mars-project.eu). We are grateful to two anonymous referees for their valuable comments and improvements on an earlier version of the manuscript.

References

Aguiar, F., Ferreira, M.T., 2005. Human-disturbed landscapes: effects on composition and integrity of riparian woody vegetation in the Tagus River basin, Portugal. Environ. Conserv. 32, 30–41.

Arabi, M., Frankenberger, J.R., Engel, B.A., Arnold, J.G., 2008. Representation of agricultural conservation practices with SWAT. Hydrol. Process. 22, 3042–3055.

Armitage, P.D., Moss, D., Wright, J.F., Furse, M.T., 1983. The performance of a new water quality score system based on macroinvertebrates over a wide range of unpolluted running-water sites. Water Res. 17, 333–347.

Basheer, A.K., Lu, H., Omer, A., Ali, A.B., Abdelgader, A.M.S., 2016. Impacts of climate change under CMIP5 RCP scenarios on the streamflow in the Dinder River and ecosystem habitats in Dinder National Park, Sudan. Hydrol. Earth Syst. Sci. 20, 1331–1353.

Birk, S., Hering, D., 2006. Direct comparison of assessment methods using benthic macroinvertebrates: a contribution to the EU water framework directive intercalibration exercise. Hydrobiologia 566, 401–415.

Bonada, N., Resh, V.H., 2013. Mediterranean-climate streams and rivers: geographically separated but ecologically comparable freshwater systems. Hydrobiologia 719, 1–29.

Bonada, N., Dolédec, S., Statzner, B., 2007. Taxonomic and biological trait differences of stream macroinvertebrate communities between mediterranean and temperate regions: implications for future climatic scenarios. Glob. Chang. Biol. 13, 1658–1671.

Buffagni, A., Erba, S., Armanini, D.G., 2010. The lentic-lotic character of Mediterranean rivers and its importance to aquatic invertebrate communities. Aquat. Sci. 72, 45–60.

Chatzinikolaou, Y., 2007. Effect of management practices on the water quality and ecology of rivers in Greece. Pinios River as a Study Case, 2007 Doctorate Thesis. Department of Biology, Aristotle University of Thessaloniki Volume A: pp. 229 and volume B, p. 470. 10.12681/eadd/20876.

Chatzinikolaou, Y., Ioannou, A., Lazaridou, M., 2010. Intra-basin spatial approach on pollution load estimation in a large Mediterranean river. Desalination 250, 118–129.

Cortes, R.M.V., Ferreira, M.T., Oliveira, S.V., Oliveira, D., 2002. Macroinvertebrate community structure in a regulated river segment with different flow conditions. River Res. Appl. 18, 267–382.

Dahm, V., Hering, D., Nemitz, D., Graf, W., Schmidt-Kloiber, A., Leitner, P., Melcher, A., Feld, C.K., 2013. Effects of physico-chemistry, land use and hydromorphology on three riverine organism groups: a comparative analysis with monitoring data from Germany and Austria. Hydrobiologia 704, 389–415.

Domisch, S., Araújo, M.B., Bonada, N., Pauls, S.U., Jähnig, S.C., Haase, P., 2013. Modelling distribution in European stream macroinvertebrates under future climates. Glob. Chang. Biol. 19, 752–762.

Dudula, J., Randhir, T.O., 2016. Modeling the influence of climate change on watershed systems: adaptation through targeted practices. J. Hydrol. 541, 703–713.

Dunbar, M.J., Pedersen, M.L., Cadman, D., Extence, C., Waddingham, J., Chadd, R., Larsen, S.E., 2010. River discharge and local-scale physical habitat influence macroinvertebrate LIFE scores. Freshw. Biol. 55, 226–242.

Elith, J., Leathwick, J.R., Hastie, T., 2008. A working guide to boosted regression trees. J. Anim. Ecol. 77, 802–813.

Feld, C.K., Hering, D., 2007. Community structure or function: effects of environmental stress on benthic macroinvertebrates at different spatial scales. Freshw. Biol. 52, 1380–1399.

Feld, C.K., Birk, S., Bradley, D.C., Hering, D., Kail, J., Marzin, A., Melcher, A., Nemitz, D., Pedersen, M.L., Pletterbauer, F., Pont, D., Verdonschot, P.F.M., Friberg, N., 2011. From natural to degraded rivers and back again. A test of restoration ecology theory and practice. Adv. Ecol. Res. 44, 119–209.

Folt, C.L., Chen, C.Y., Moore, M.V., Burnaford, J., 1999. Synergism and antagonism among multiple stressors. Limnol. Oceanogr. 44, 864–877.

Gasith, A., Resh, V.H., 1999. Streams in Mediterranean regions: abiotic influences and biotic responses to predictable seasonal events. Annu. Rev. Ecol. Syst. 30, 51–81.

Graeber, D., Pusch, M.T., Lorenz, S., Brauns, M., 2013. Cascading effects of flow reduction on the benthic invertebrate community in a lowland river. Hydrobiologia 717, 147–159.

Grover, V.I., 2015. Impact of climate change on the water cycle. In: Shrestha, S., Anal, A., Salam, P., van der Valk, M. (Eds.), Managing Water Resources under Climate Uncertainty. Springer Water. Springer, Cham.

Hale, R., Piggott, J.J., Swearer, S.E., 2017. Describing and understanding behavioral responses to multiple stressors and multiple stimuli. Ecol. Evol. 7, 38–47.

Hering, D., Carvalho, L., Argiller, C., Beklioglu, M., Borja, A., Cardoso, A.C., Duel, H., Ferreira, T., Globevnik, L., Hanganu, J., Hellsten, S., et al., 2015. Managing aquatic ecosystems and water resources under multiple stress - an introduction to the MARS project. Sci. Total Environ. 503-504, 10–21.

Hershkovitz, Y., Gasith, A., 2013. Resistance, resilience, and community dynamics in mediterranean-climate streams. Hydrobiologia 719, 59–75.

Hijmans, R.J., Phillips, S., Leathwick, J., Elith, J., 2013. Species Distribution Modelling. Package "dismo". Available at:. http://cran.r-project.org/web/packages/dismo/dismo.pdf.

Hooke, J.M., 2006. Human impacts on fluvial systems in the Mediterranean region. Geomorphology 79, 311–335.

IPCC, 2013. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M. (Eds.), Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA (1535 pp.).

Johnson, R.K., Hering, D., 2009. Response of taxonomic groups in streams to gradients in resource and habitat characteristics. J. Appl. Ecol. 46, 175–186.

Kriegler, E., O'Neill, B.C., Hallegatte, S., Kram, T., Lempert, R., Moss, R., Wilbanks, T., 2012. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socioeconomic pathways. Glob. Environ. Chang. 22, 807–822.

Kuemmerlen, M., Schmalz, B., Cai, Q., Haase, P., Fohrer, N., Jähnig, S.C., 2015. An attack on two fronts: predicting how changes in land use and climate affect the distribution of stream macroinvertebrates. Freshw. Biol. 60, 1443–1458.

Lakew, A., Moog, O., 2015. A multimetric index based on benthic macroinvertebrates for assessing the ecological status of streams and rivers in central and southeast highlands of Ethiopia. Hydrobiologia 751, 229–242.

Liuzzo, L., Noto, L.V., Arnone, E., Caracciolo, D., La Loggia, G., 2015. Modifications in water resources availability under climate changes: a case study in a Sicilian basin. Water Resour. Manag. 29, 1117–1135.

Mariotti, A., Zeng, N., Yoon, J.-H., Artale, V., Navarra, A., Alpert, P., Li, L.Z.X., 2008. Mediterranean water cycle changes: transition to drier 21st century conditions in observations and CMIP3 simulations. Environ. Res. Lett. 3 (2008), 044001.

Milly, P.C., Dunne, K.A., Vecchia, A.V., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438, 347–350.

Mimikou, M., Baltas, E., 2013. Assessment of climate change impacts in Greece: a general overview. AJCC 3, 46–56.

Mimikou, M., Baltas, E., Varanou, E., Pantazis, K., 2000. Regional impacts of climate change on water resources quantity and quality indicators. J. Hydrol. 234, 95–109.

Molina-Navarro, E., Trolle, D., Martínez-Pérez, S., Sastre-Merlín, A., Jeppesen, E., 2014. Hydrological and water quality impact assessment of a Mediterranean limno-reservoir under climate change and land use management scenarios. J. Hydrol. 509, 354–366.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2009. Soil and Water Assessment Tool (SWAT) Theoretical Documentation. Blackland Research Center, Texas. Agricultural Experiment Station, Temple, Texas (BRC Report 02–05). Available online at. http://swatmodel.tamu.edu/documentation.

Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for community action in the field of water policy. Off. J. Eur. Communities 1–77 (L327, 22.12.2000).

O'Neill, B.C., et al., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic reference pathways. Clim. Chang. 112, 387–400.

Ormerod, S.J., Dobson, M., Hildrew, A.G., Townsend, C.R., 2010. Multiple stressors in freshwater ecosystems. Freshw. Biol. 55, 1–4.

Panagopoulos, Y., Makropoulos, C., Mimikou, M., 2011. Diffuse surface water pollution: driving factors for different geoclimatic regions. Water Resour. Manag. 25, 3635–3660.

Panagopoulos, Y., Makropoulos, C., Mimikou, M., 2012. A multi-Objective Decision Support Tool for Rural Basin Management. International Environmental Modelling and Software Society (iEMSs), International Congress on Environmental Modelling and Software, Managing Resources of a Limited Planet: Pathways and Visions under Uncertainty, Leipzig, Germany (1–5 July 2012).

Panagopoulos, Y., Makropoulos, C., Kossida, M., Mimikou, M., 2013. Optimal implementation of irrigation practices: a cost effective desertification action plan for Pinios. J. Water Res. Pl-Asce140, 05014005.

Panagopoulos, Y., Makropoulos, C., Gkiokas, A., Kossida, M., Evangelou, E., Lourmas, G., Michas, S., Tsadilas, C., Papageorgiou, S., Perleros, V., Drakopoulou, S., Mimikou, M., 2014. Assessing the cost-effectiveness of irrigation water management practices in water stressed agricultural catchments: the case of Pinios. Agric. Water Manag. 139, 31–42.

Papadaki, C., Soulis, K., Muñoz-Mas, R., Martinez-Capel, F., Zogaris, S., Ntoanidis, L., Dimitriou, E., 2016. Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. Sci. Total Environ. 540, 418–428.

Paparrizos, S., Maris, F., Matzarakis, A., 2016. Integrated analysis of present and future responses of precipitation over selected Greek areas with different climatic conditions. Atmos. Res. 169, 199–208.

Psomas, A., Dagalaki, V., Panagopoulos, Y., Konsta, D., Mimikou, M., 2016. Sustainable water management in Pinios river basin using remote sensing and hydrological modelling. Procedia Eng. 162, 277–283.

R Core Team, 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria URL. https://www.R-project.org/.

Sandin, L., Hering, D., 2004. Comparing macroinvertebrate indices to detect organic pollution across Europe: a contribution to the EC water framework directive intercalibration. Hydrobiologia 516, 55–68.

Santos, R.M.B., Sanches Fernandes, L.F., Varandas, S.G.P., Pereira, M.G., Sousa, R., Teixeira, A., Lopes-Lima, M., Cortes, R.M.V., Pacheco, F.A.L., 2015. Impacts of climate change and land-use scenarios on *Margaritifera margaritifera*, an environmental indicator and endangered species. Sci. Total Environ. 511, 477–488.

Scoccimarro, E., Gualdi, S., Bellucci, A., Zampieri, M., Navarra, A., 2016. Heavy precipitation events over the Euro-Mediterranean region in a warmer climate: results from CMIP5 models. Reg. Environ. Chang. 16, 595–602.

Sellami, H., Benabdallah, S., La Jeunesse, I., Vanclooster, M., 2016. Quantifying hydrological responses of small Mediterranean catchments under climate change projections. Sci. Total Environ. 543, 924–936.

Sheffield, J., Wood, E.F., 2008. Projected changes in drought occurrence under future global warming from multi-model, multi scenario, IPCC AR4 simulations. Clim. Dyn. 31, 79–105.

Shrestha, M.K., Recknagel, F., Frizenschaf, J., Meyer, W., 2017. Future climate and land uses effects on flow and nutrient loads of a Mediterranean catchment in South Australia. Sci. Total Environ. 590–591, 186–193.

Skoulikidis, N., Karaouzas, I., Gritzalis, K., 2009. Identifying key environmental variables structuring benthic fauna for establishing a biotic typology for Greek running waters. Limnologica 39, 56–66.

Soria, M., Leigh, C., Datry, T., Bini, L.M., Bonada, N., 2017. Biodiversity in perennial and intermittent rivers: a meta-analysis. Oikos 126, 1078–1089.

Stefanidis, K., Panagopoulos, Y., Mimikou, M., 2016. Impact assessment of agricultural driven stressors on benthic macroinvertebrates using simulated data. Sci. Total Environ. 540, 32–42.

SWAT, 2013. ArcSWAT: ArcGIS-ArcView Extension and Graphical User Input Interface for SWAT. U.S. Department of Agriculture, Agricultural Research Service, Grassland, Soil & Water Research Laboratory, Temple, TX http://swat.tamu.edu/software/arcswat/.

Tolika, C.K., Zanis, P., Anagnostopoulou, C., 2012. Regional climate change scenarios for Greece: future temperature and precipitation projections from ensembles of RCMs. Glob. Nest J. 14, 407–421.

Van Vuuren, D., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J., Rose, S.K., 2011. The representative concentration pathways: an overview. Clim. Chang. 109, 5–31.

Villeneuve, B., Souchon, Y., Ussegio-Polatera, P., Ferréol, M., Valette, L., 2015. Can we predict biological condition of stream ecosystems? A multi-stressors approach linking three biological indices to physico-chemistry, hydromorphology and land use. Ecol. Indic. 48, 88–98.

Vörösmarty, C.J., McIntyre, P.B., Gessner, M.O., et al., 2010. Global threats to human water security and river biodiversity. Nature 467, 555–561.

Waddle, T.J., Holmquist, J.G., 2013. Macroinvertebrate response to flow changes in a subalpine stream: predictions from two-dimensional hydrodynamic models. River Res. Appl. 29, 366–379.

Zheng, F.L., Huang, C.H., Norton, L.D., 2004. Effects of near-surface hydraulic gradients on nitrate and phosphorus losses in surface runoff. J. Environ. Qual. 33, 2174–2182.